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Gaseous products and particulate matter emissions of biomass residential boiler fired with spent coffee grounds pellets

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HIGHLIGHTS

- Agropellets produced from spent coffee grounds or blended with pine sawdust.
- Agropellets physicochemical characteristics and energy contents were determined.
- Combustion performances, gaseous and particulate emissions of pellets boiler.
- Although an interesting energy content, pure SCG is not adapted for pellets boiler.
- Sawdust/SCG blend is an attractive alternative fuel to reach NF agro-pellets label.

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ABSTRACT

In this present work, energetic characteristics and combustion behavior of agro-pellets, produced from pure spent coffee grounds (SCGs) or blended with pine sawdust in a commercial residential pellet boiler, were examined. Hence, thermal and chemical properties such as calorific value, ash content, bulk density, fixed carbon and elemental analysis obtained from blend and pure biomasses were firstly examined. Moreover, combustion tests were performed in 8–12 kW Okofen Boiler, carbon monoxide (CO) and volatile organic compounds (VOCs) were analyzed according to French standards. The emissions of some gases were also monitored during combustion tests: O_2, CO_2, NO and NO_2. An Electrical Low Pressure Impactor (ELPI) was used to collect particles from 29 nm to 10 μm into 12 size fractions to determine mass and number concentrations. The exhaust gaseous and particles emissions of SCG and blend pellets were compared with emissions of wood pellets (DIN + standard).

It was found that, despite its high LHV, the use of pure SCG as fuel lead to a lower boiler efficiency, which was followed by an increase of particle and gas emissions. However, when SCG was mixed with pine sawdust (50/50 wt.%), combustion parameters (emissions and boiler efficiency) were very close to those obtained for wood pellets.

According to the presented results, although it seems reasonable to consider SCG pellets as a promising alternative fuel, the use of SCG blending up to 50% with pine sawdust is essential to meet French Standards (NF agro-pellets). Hence, this pellets production may be a promising issue for SCG valorisation.

1. Introduction

The use of renewable bioresources as energy sources or an alternative of fossil-based feedstock has received, recently, much attention. Biomass in general and agro-industrial residues in particular seem to be realistic alternative fuels leading to environmental, technical and economical benefits. Coffee is one of the most important agricultural commodities in the world and is the second largest traded commodity after petroleum [1]. Therefore, coffee industry is responsible for the generation of large amount of residues [2]. Among these residues, coffee processing generates about 6 million tons of spent coffee grounds (SCGs) [3]. SCG is a solid residue with fine particle size, high humidity (in the range of 80–85%), organic load, and acidity, obtained during the treatment of raw coffee powder with hot water or steam for instant coffee preparation [1]. SCG is a residue rich in sugars polymerized into cellulose and hemicellulose structures, which correspond to almost half of material dry weight (45.3% w/w). Hemicellulose is composed by three sugars, mannose (21.2% w/w), galactose (13.8% w/w), and arabinose (1.7% w/w) while cellulose is composed by glucose (8.6% w/w) [4]. In addition to polysaccharides, SCG also contains

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significant protein content (13.6% w/w) mainly glutamic acid (6.2–9.9 mg/g), leucine (5.6–7.8 mg/g), glycine (1.3–5.7 mg/g), valine (3.2–4.9 mg/g), phenylalanine (0.3–4.8 mg/g) and alanine (2.6–3.9 mg/g) [4]. Moreover, SCG also contains ashes constituted by several minerals such as potassium (3.5 mg/g), phosphorus (1.5 mg/g), magnesium (1.3 mg/g) and calcium (0.8 mg/g) [4].

Due to the presence of different organic materials, SCG is a highly pollutant residue and demands great quantities of oxygen to degrade [5]. In addition, caffeine, tannins, and polyphenols present in these materials confer a toxic nature. Therefore, SCG represents a pollution hazard if discharged into the environment. Despite this negative characteristic and the large amounts generated, few studies have focused on SCG valorisation in advantageous applications. The possibility of SCG use as animal feed for ruminants, pigs, chickens, and rabbits [6,7] soil conditioner and organic fertilizer [6] has been already verified. Further reused as a potential feedstock to produce useful products such as enzymes, organic acids, flavors and aroma compounds have been also evaluated [8]. Several attempts for energy production from SCG use have been tested. In particular, Kondamudi et al. have demonstrated that SCG can be used as a potential source to produce biodiesel and fuel pellets, among other value-added products, such as H_2 and ethanol [9]. Recently, SCG was evaluated as a potential feedstock for preparing biochar fuel [10]. Authors have shown that biochar derived from exhausted coffee residue (ECR) may be used as a solid fuel in the industrial sector as an alternative for coal [10]. The use of SCG as fuel in industrial boilers was already performed in the coffee industry due to its high calorific power of approximately 5000 kcal/kg, which is comparable with other agro-industrial residues [5]. However, the generation of particulate matter, which may affect air quality near the industry was observed.

In the last decade, several researchers have published papers on the combustion behavior of different biomass residue pellets in domestic boilers [11–16]. Gonzalez et al. have examined combustion parameters of tomato, cardoon, forest pellets and olive stone in a 12 kW mural boiler for domestic heating [11]. They noted that the tested biomass residues use in the domestic boiler were acceptable. Boiler efficiencies obtained with the maximum fuel mass flow (100%) and minimum draught (0%) were 90%, 90.5%, 89.7% and 91.6% for tomato, forest, olive stone and cardoon pellets, respectively. Moreover, they have found that tomato pellets and olive stones are excellent substitutes to forest pellets recommended by manufacturers in comparison with cardoon pellets. The latter presents a high ash content (with a low melting point) which requires their continual removal from the fireplace [11]. In a second study, authors have examined in the same conditions the combustion parameters of almond residues (almond tree pruning, almond shell, and almond peel) [12]. Boiler efficiencies were 88.3%, 85%, 78.5% for almond tree pruning, almond shell, and almond peel, respectively. They noted that the use of an almond tree pruning (75%) and forest pellet (25%) mixture gave more efficient combustion processes [12].

Verma et al. investigated the use of a 40 kW boiler for the combustion of eight types of pellets stemming from agriculture and wood residues namely apple pomace (*Malus domestica*), reed canary grass (*Phalaris arundinacea*), pectin waste from citrus shells (*Citrus reticulata*), sunflower husk (*Helianthus annuus*), peat, wood and two types of wheat straw pellets (*Triticum aestivum*) [13]. Authors have found that under standard laboratory conditions, boiler efficiency was higher with wood and apple pellets. Apple, reed canary grass and citrus pectin waste pellets have lower emissions in comparison other agro-pellets. Particle emissions were higher with sunflower husk pellets (654.7 mg Nm^{-3}). In previous investigations, Verma et al. have performed a comparative study on the combustion emissions of these residues. Authors found that the boiler satisfied emissions (except CO with peat pellets and dust with peat and sunflower husk pellets) and efficiency requirements of the EN-303-5 standard with each agro-pellet formulations. However, they noted that the high ash content (with a low melting point of straw pellets was unsuitable for this kind of domestic applications [14,15].

Recently, Miranda et al. have examined the characterization and combustion of olive pomace, forest residue and their blend pellets [16]. They showed that during pellets combustion, emissions were slightly worse with pure olive pomace pellets, concluding that it was not recommendable to use blends with more than 50% of this product [16].

Previous investigations showed that the study of agro-pellets combustion behavior and biomass boilers optimization was a hot topic for research. Hence, in this present work, an attempt is performed to analyze the energetic characteristics and the densification properties of agro-pellets produced from a pure SCG as well as a blend of SCG with pine sawdust. Combustion behavior, gaseous and particle emissions are also examined by using a domestic pellet boiler.

2. Materials and methods

2.1. Sample preparation

SCG powder, provided by a coffee processing in the east of France (Sotoco, Mulhouse-France), was transformed into pellets with 6 mm diameter and 15–25 mm length approximately using KAHL 14/175 pelletizer. SCG and pine sawdust were pelletized after being dried and rehydrated to a well-known extent. The first objective was to prepare a pelletized biomass fuel with properties close to the superior NF agro-pellets standard. Initial moisture of SCG was set at 12% while it was set at 10% for pine sawdust. Experimental pelletizing conditions were different because SCG average particle size was close to 0.6 mm while sawdust sample particle size was defined between 2 and 4 mm. Then, SCG was pelletized with a 26 mm length screwing die at 50 Hz and at 70 °C, while pine sawdust was pelletized with a 18 mm length screwing die at 50 Hz and at 80 °C. SCG/pine sawdust blend was prepared using a 22 mm length screwing die at 50 Hz at 80 °C. Blend of SCG and pine sawdust (Picea) was prepared using a 50/50 mass proportion to reach the superior NF agro-pellets standard requirements (LHV = 15.8 kJ/kg, ash < 5 wt.%, N < 1.5 wt.% and S < 0.2 wt.%). This point was essential since it allowed considering the possibility to sell this new biomass fuel in the French market.

2.2. Sample characterizations

2.2.1. Proximate and ultimate analysis

Ultimate analyses corresponding to the elemental composition of crude SCG and sawdust were carried out by Service Central d'Analyses (Vernaison, France) to determine the weight fraction of carbon, hydrogen, nitrogen, sulfur and chlorine. Ultimate analyses were made on wet basis (35.71% of moisture for pure SCG and 17.61% for pine sawdust). Elemental compositions of SCG and pine sawdust are given on dry basis in Table 1. Oxygen content was determined by difference (taking into account ash content and moisture). Proximate analyses were conducted using a thermogravimetric analyzer (CAHN 121). The proximate TG method involves heating the sample (under N_2) at a rate of 10 °C/min to 110 °C then holding for 10 min to obtain the weight loss associated with moisture. The temperature is then ramped from 110 °C at a rate of 20 °C/min to 900 °C (under N_2) and held for 10 min to obtain the weight loss associated with volatiles release. Air is then introduced into the furnace chamber to oxidize the carbon present in the char. The corresponding weight loss is associated to the fixed